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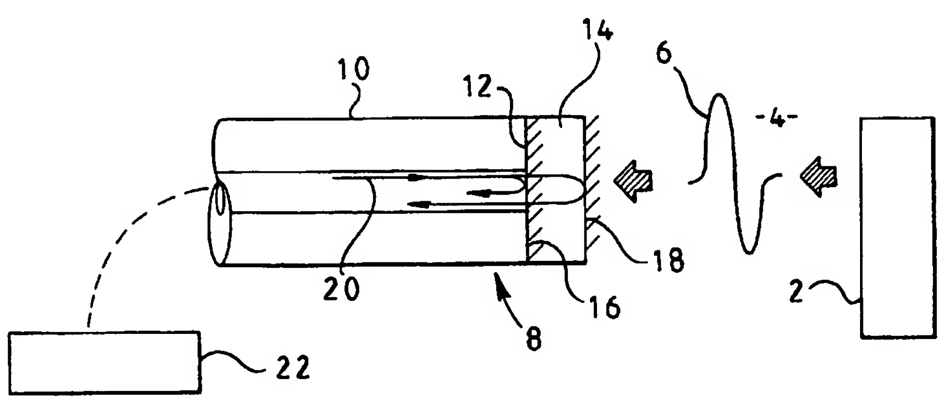
(54) Title: FABRY PEROT SINGLE MODE FIBRE INTERFEROMETER



(57) Abstract: An optical fibre interferometer for sensing an incident wave comprises an optical fibre (10) and a polymer film (14) against one end (12) of the fibre. The two opposite faces (16, 18) of the polymer film provide reflecting surfaces of the interferometer, and the optical thickness of the film is modulated by the incident wave (6). The optical fibre (10) comprises a single mode fibre. The device has good stability and small active area, enabling omnidirectional response, even at high frequencies.

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FABRY PEROT SINGLE MODE FIBRE INTERFEROMETER

This invention relates to optical fibre interferometers, particularly, but not exclusively, for use in a hydrophone for detecting pressure variations caused by the propagation of acoustic waves.

A known optical fibre hydrophone using an interferometer is described in the article "Miniature optical fibre ultrasonic hydrophone using a Fabry-Perot polymer film interferometer" by P C Beard and T N Mills published in Electronics Letters 24 April 1997, Volume 33 No. 9. This article describes an interferometer arrangement in which a polymer sensing film is provided at a cleaved end of the fibre, two opposite faces of the polymer film providing the two reflecting surfaces of the interferometer. An incident acoustic wave modulates the thickness of the film which influences the output of the interferometer. The hydrophone uses a multi-mode fibre, which does not require high alignment tolerances. However, mode coupling within a multi-mode fibre gives rise to non-uniform fibre characteristics and thereby degrades the performance of the sensing device.

Optical fibre hydrophones of this type may be used for monitoring any source of acoustic signals or characterising acoustic signals propagating within a sample of interest. For example, the hydrophone may be used to monitor, analyse or tune the operation of an ultrasonic cleaning system. Alternatively, hydrophones may be used for analysing acoustic signals used to study biological tissue in medical examination equipment. Also, thermal signals may modulate the optical thickness of the sensing film and can therefore be detected by the hydrophone.

According to the present invention, there is provided an optical fibre interferometer for sensing an incident wave comprising an optical fibre and a polymer film against one end of the fibre, two opposite faces of the polymer film providing reflecting surfaces of the interferometer, the optical thickness of the film being modulated by the incident wave, and wherein the optical fibre comprises a single mode fibre.

The use of a single mode fibre improves the stability of the interferometer, and enables the interferometer to have a small active area (corresponding to the mode field diameter of the

fibre), preferably of width less than $15\mu m$, and preferably around $10\mu m$. This enables the interferometer to detect input signals of a wide range of wavelengths at non-normal angles of incidence. In particular, omnidirectional response can be achieved at high frequencies, for example to detect oblique signals having wavelengths as small as $20\mu m$.

The output of a single mode fibre has a power distribution which may be approximated as a Gaussian beam, and propagates with a diffraction-limited profile. Consequently, the output from the single mode fibre close to the fibre tip has a limited divergence profile. In the interferometer arrangement of the invention, with the polymer film butted against the distal end of the fibre, the diffraction-limited divergence of the output profile enables high finesse operation to be achieved.

For this purpose, the face of the polymer film against the fibre may be associated with a coating giving rise to a reflectivity of between 70% and 95%, and the other face of the polymer film may be associated with a coating giving rise to a reflectivity of approximately 100%. These coatings result in the formation of a highly resonant optical cavity.

The coatings may be provided on the respective faces of the polymer film and may comprise dielectric coatings.

The interferometer is preferably used as a hydrophone for detecting incident acoustic waves. Such acoustic waves may be used in numerous applications. Taking as one example the use of ultrasound in medical ultrasound equipment, the signals may typically have frequencies between 0.5 and 50 MHz. The corresponding wavelengths of acoustic signals in fresh water are 2.8mm and $28\mu m$ (taking the speed of sound in fresh water to be 1410m/s). The interferometer of the invention can be arranged to detect these signals for all angles of incidence.

The invention will now be described by way of example, with reference to and as shown in the accompanying drawings in which:

Figure 1 shows an interferometer of the invention and represents the use of the interferometer

in medical ultrasound equipment by way of example;

Figure 2 shows the diffraction-limited propagation of an optical beam having a Gaussian distribution; and

Figure 3 illustrates some preferred dimensions for the components of the interferometer of Figure 1.

Optical fibre interferometers are well-known for measuring physical parameters. This invention is particularly directed to a measurement device operating according to the principles of a Fabry-Perot interferometer. Such a device may be used to study signals generated from any ultrasound source, and for any purpose, but Figure 1 illustrates medical ultrasound equipment by way of example.

In general terms, the equipment comprises an excitation source 2 which produces a signal which is modified by a sample 4 to produce a signal 6 representing a physical parameter of the sample 4, the signal 6 being detectable by the interferometer device 8.

The interferometer comprises an optical fibre having a cleaved and polished end face 12. Butted against the end face 12 is a polymer film 14 having opposite parallel faces 16, 18 which are least partially reflective to incident light from a given direction (from left to right in Figure 1). The face 16 is partially reflective so that some of the interrogation source signal is able to penetrate into the polymer film 14, and the face 18 may be 100% reflective.

An optical signal 20 is supplied to the optical fibre 10 by a light source and detector assembly 22. Light is reflected from the two faces 16, 18. The signal 6 modulates the thickness of the film 14 and hence the optical phase difference between the light reflected from the two faces 16, 18. This produces a corresponding intensity modulation of the light reflected from the film 14. For optimum sensitivity and linearity, the interferometer should be operated at a phase bias that corresponds to quadrature. In other words, the phase bias is set half way between the maximum and the minimum of the interferometer transfer function.

There are, of course, various other schemes for interrogating interferometers. For example,

instead of this narrowband approach, a broadband low coherence technique may be employed, when the spectral content of the reflected signal is analysed, using another receiving interferometer.

The operation of the apparatus shown in Figure 1 is known, to the extent described above. The signal 6 may comprise an acoustic wave, which carries information to be monitored. In the specific example of medical ultrasound equipment as shown in Figure 1, the characteristics of the acoustic wave may give information concerning a biological sample being examined. Alternatively, in the example of ultrasonic cleaning equipment, the presence of the acoustic signal may be used to indicate that the ultrasound cleaning system is operating correctly. There are numerous other possible applications.

In the example of Figure 1, the excitation source 2 may comprise an ultrasound source for imaging or treatment, and the interferometer may then be provided for taking safety-related exposure measurements. Alternatively, the excitation source may comprise a source of laser excitation pulses which are absorbed in a target absorber, resulting in the production of acoustic and thermal waves. These waves may be detected by the sensor as a result of a change to the optical thickness of the film, and therefore the optical phase difference between the reflected signals.

In accordance with the invention, the optical fibre 10 comprises a single mode fibre. This enables the interferometer to have a small active area. Furthermore, the provision of the film 14 butted against the end of the fibre enables the low divergence close to the exit of the single mode fibre to be utilized to form a high finesse device. The widespread availability and low cost of the components required to form the interferometer enable it to be disposable, whilst having high performance.

Figure 2 shows the diffraction-limited propagation of a Gaussian beam. The shaded area in Figure 2 represents the area within which the power density profile ranges from $1/e^2$ to 1 times the peak power density. The radius r_0 is the radius at which the power density distribution is $1/e^2$ times the peak. This radius is approximately equal to the radius of the core 11 of the single mode fibre, since part of the energy of the beam propagates in the

cladding of the fibre. The Gaussian profile is representative of the output power distribution of the fundamental transverse mode of oscillation of a cylindrical laser source and of the single mode carried by the single mode fibre.

As shown in Figure 2, the envelope 30 of the optical output diverges at a uniform rate from a point 32 at the centre of the fibre output. The rate of divergence is a function of the light wavelength λ as well as the radius r_0. Within an initial distance l_0 the outer envelope 34 maintains a substantially constant size so that limited divergence takes place.

The active area of the interferometer corresponds to the mode field diameter, which is the diameter of the shaded area in Figure 2.

If the input signal 6 is received perpendicularly to the faces 16, 18, as represented schematically in Figure 1, the active area is of less significance and the measuring device will be responsive to the input signal 6 provided the detector assembly 22 has sufficient frequency response. However, if the input signal 6 is received at an angle to the faces 16, 18 then the interferometer will integrate the input signal over the active area of the measuring device. Therefore, for detection of input signal 6 oblique to the faces 16, 18, the active area of the measuring device must extend over a distance which is small in relation to the wavelength of the signal 6 to be measured.

As mentioned above, in one application of the invention, the measurement signal 6 comprises an acoustic wave of frequency up to around 50MHz. In this medical use of the apparatus, the device will be positioned within an area of interest of a patient's body and for the purposes of illustration, we shall assume that the acoustic wave travels with the speed of sound in pure water, which is 1410m/s. At 50MHz, this corresponds to a wavelength of 28.2μm.

To enable omnidirectional detection of a 50MHz acoustic wave, an active area of less than approximately 10μm is appropriate, and this is achievable with a single mode fibre. The polymer film 14 may have a thickness of approximately 10μm, which is less than the distance l_0 within which the divergence of the beam from the output of the fibre remains

limited. A high finesse device can thus be formed.

To form a high finesse device, low absorption coatings on the opposite faces of the polymer film 14 are required. For example, dielectric coatings may be used. The coating on the face 16 may have reflectivity approaching (but not exceeding) 100%, for example 95%, whereas the coating on the face 18 is preferably arranged to be as close to 100% reflective as possible (for the optical signal 20).

The limited divergence of the envelope 34 enables multiple reflections of the light signal 20 to take place within the cavity defined by the polymer film 14, as illustrated schematically in Figure 3. This resonance improves the sensitivity of the interferometer. Thus, high finesse operation compensates for the smaller acoustically induced phase shifts across the film resulting from the small thickness of the film 14. With a multi-mode fibre, phase dispersion due to the divergent nature of the optical illumination prevents high finesse operation.

As one example, the core 36 of the optical fibre 10 has an approximate diameter of $6\mu m$, the core being surrounded with an appropriate depth of cladding 38, for example having an outside diameter of $125\mu m$, and an outer buffer giving a total outside diameter of $250\mu m$.

The small active area of the interferometer also facilitates the production of a polymer film 14 having extremely parallel and uniform faces 16, 18 over the area of interest. The sensing film may comprise a disc of PET (polyethylene terepthalate). Such discs may be cut from a larger film, and the smaller the required area the more uniform will be the film thickness.

An additional advantage of the use of a single mode fibre is that mode crossings may be avoided and that the power distribution within the fibre is more uniform.

The design of the light source and detector assembly 22 as well as of the excitation source 2 will be apparent to those skilled in the art. As one example, the light source may comprise a tunable laser diode, which may produce light of around 850nm. The detector assembly within unit 22 may comprise a photodiode having an integral transimpedance amplifier. The laser source may be tuned to obtain quadrature operation of the interferometer. The various

possible applications to which the interferometer design of the invention may be put will determine the specific design of excitation source 2. Some of the possibilities have been described above.

Claims

1. An optical fibre interferometer for sensing an incident wave comprising an optical fibre and a polymer film against one end of the fibre, two opposite faces of the polymer film providing reflecting surfaces of the interferometer, the optical thickness of the film being modulated by the incident wave, and wherein the optical fibre comprises a single mode fibre.

2. An interferometer as claimed in claim 1 having an active area of width less than $15\mu m$.

3. An interferometer as claimed in any preceding claim, wherein the thickness of the polymer film is less than or equal to $15\mu m$.

4. An interferometer as claimed in any preceding claim, wherein the face of the polymer film against the fibre is associated with a coating giving rise to a reflectivity of between 70% and 95%, and the other face of the polymer film is associated with a coating giving rise to a reflectivity of approximately 100%.

5. An interferometer as claimed in claim 4, wherein the coatings are provided on the respective faces of the polymer film and comprise dielectric coatings.

6. A hydrophone comprising an interferometer as claimed in any preceding claim, wherein an incident acoustic wave modulates the thickness of the polymer film.

7. Medical ultrasound equipment comprising an excitation source and an ultrasound detector comprising a hydrophone as claimed in claim 6.

8. Medical ultrasound equipment as claimed in claim 7, wherein the excitation source results in the generation of electromagnetic radiation of frequency up to 50 MHz.

FIG 1

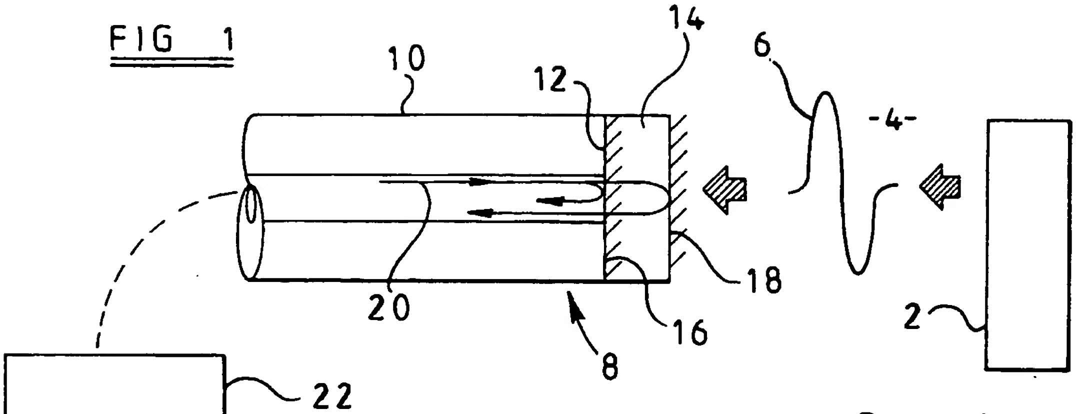
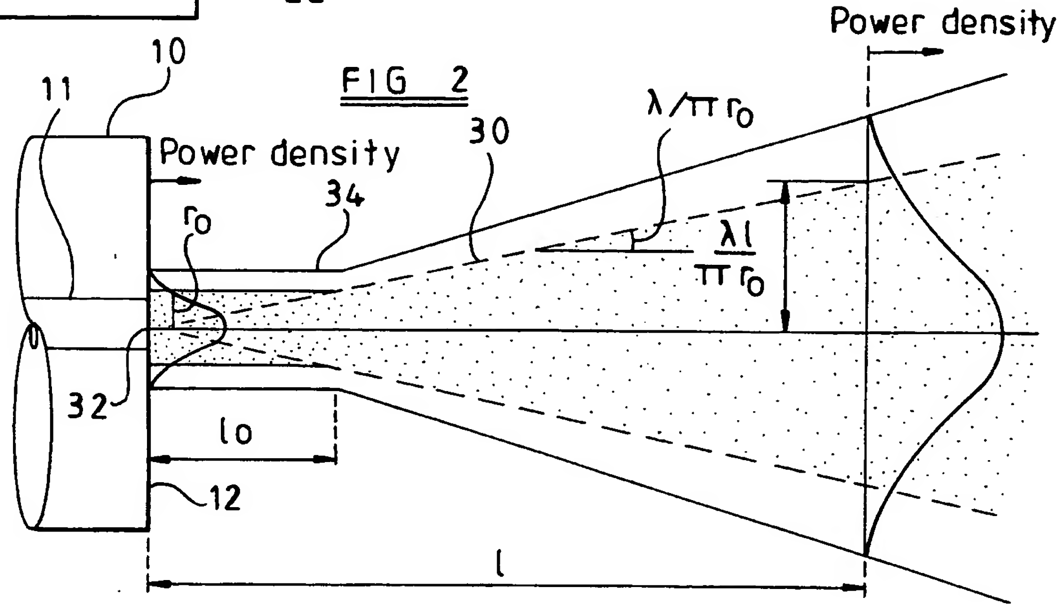


FIG 2



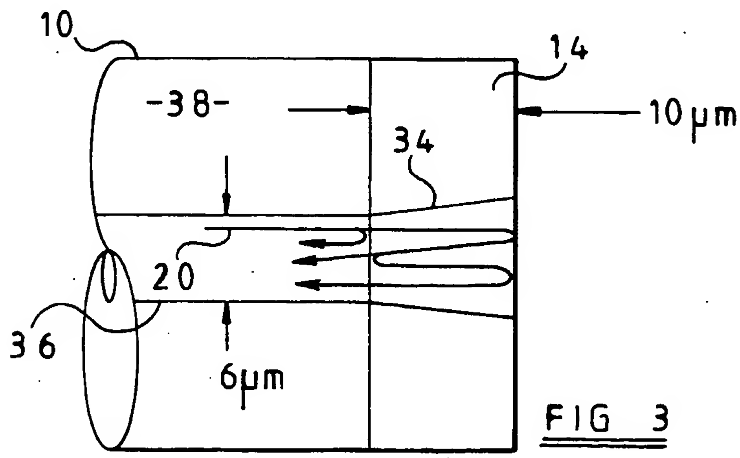


FIG 3

INTERNATIONAL SEARCH REPORT

Inter | Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01H9/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DE 195 41 952 A (KOCH) 15 May 1997 (1997-05-15) claims 1,4	1
A	P.C.BEARD AND T.N.MILLS: "Miniature optical fibre ultrasonic hydrophone using a Fabry Perot polymer film interferometer" ELECTRONICS LETTERS, vol. 33, no. 9, 24 April 1997 (1997-04-24), pages 801-803, XP000695342 cited in the application figure 1	1-8
A	US 5 311 485 A (USA) 10 May 1994 (1994-05-10) column 3, line 6; figure 1	

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
12 September 2000	22/09/2000

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Inter. l Application No
PCT/GB 00/02495

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	V.WILKENS AND CH.KOCH: "Fiber optic multilayer hydrophone for ultrasonic measurement" ULTRASONICS, vol. 37, 1 January 1999 (1999-01-01), pages 45-49, XP004154492 figure 1	
A	CH.KOCH: "Coated fiber optic hydrophone for ultrasonic measurement" ULTRASONICS, vol. 34, 1 June 1996 (1996-06-01), pages 687-689, XP000627319 figure 1	

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter. l Application No
PCT/GB 00/02495

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE 19541952 A	15-05-1997	NONE	
US 5311485 A	10-05-1994	NONE	